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Interference-aware scheme to improve distributed caching in cellular networks via D2D underlay communications

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Abstract Underlay Device-to-Device (D2D) communications is a promising networking technology intended to boost the spectral efficiency of future cellular networks, including 5G and beyond. When used for distributed caching, where cellular devices store popular files for direct exchange later with other devices, away from the cellular infrastructure, the technology bears more fruits such as enhancing throughput, reducing latency and offloading the infrastructure. However, due to their non-orthogonality, underlay D2D communications can result in excessive interference to the cellular user. To avoid this problem, the present article proposes a scheme with two interference-reduction elements: a guard zone intended to allow D2D communications only for devices far enough from the base station (BS), and a pairing strategy intended to allow D2D communications between devices that are close enough to each other. We assess the performance of the scheme using a stochastic geometry (SG) model, through which we characterize the coverage probability of the cellular user. This probability is a principal indicator of maintaining the quality of service (QoS) of the cellular user and of enabling successful caching for the D2D user. We introduce in the process a novel empirical technique which, given a desired level of interference, identifies an upper bound for the distance between two devices to be paired without exceeding that level. We finally validate the analytical findings obtained from the model by intensive simulation to ensure the correctness of the model and the superior performance of the scheme. A salient feature of the scheme is that it requires for its implementation no software or hardware modification in the device.

Keywords Stochastic geometry, Cellular communications, Distributed Caching, Coverage probability, D2D

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1. Introduction

The popularity of on-demand multimedia, such as video streaming, has increased the overall Internet traffic volume exponentially. As of 2023, almost 82% of this global Internet traffic comes from video transmissions, changing the Internet paradigm from location-based to content-based [1]. This has led to what is called Information Centric Networking (ICN), which focuses on content distribution rather than node location. As consequence, Internet Service Providers (ISP) are beginning to implement local content caching systems for faster delivery and reduced latency and unnoticeable jitter or distortions. ICN can be implemented over a Software-Defined Networking (SDN) infrastructure. SDN enables flexible programming and implementation of forwarding packet rules within a network domain seamlessly.

One option to support distributed caching is to employ Mobile Edge Computing (MEC) servers can be used to offer storage and computing capacities to handle videos close to end-users [2]. However, this option poses high load, especially in peak hours, consuming huge amounts of the bandwidth that would otherwise serve existing cellular and backhaul links. Hence, an elastic option is required, whereby the high Quality of Experience (QoE) is

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maintained as the resource demands increase. This option is simply caching popular videos at mobile devices via direct device to device (D2D) communications, which is the theme of this article.

D2D communications can be implemented in one of two modes, overlay or underlay [3]. In the overlay mode, the D2D communications take place on frequencies other than those of the cellular network. However, as frequencies are a scarce resource, this orthogonal mode is less attractive than the underlay mode. In the underlay mode, considered in this article, D2D communications share the frequencies of the cellular network, leading to improved spectral efficiency. However, this non-orthogonal mode causes interference with the cellular user. The point of impact of the interference differs depending on whether the downlink or uplink frequencies are shared. In the downlink case, the interference will be at the cellular user equipment (UE). This interference can be very harmful if the D2D device is in close proximity to the cellular UE, which is inevitable due to the constant mobility of users. By contrast, in the uplink case, considered in this article, the interference will be at the base station (BS). This interference is usually small since the BS is stationary and far from the D2D device on the one hand, and the D2D transmit power is typically low on the other hand. Still, it can be made even smaller With the help of interference aware schemes, such as the one proposed in this article.

Even though the most common use of D2D communications is in distributed caching, communication links can be spontaneously activated and dropped depending on users' relative positions [4]. A user can request file by broadcasting a message, for example, only to find that the file as available at a neighbor user. They can then establish a communications session and exchange the file. It should be noted, however, that caching and D2D are not necessarily always tied to each other. That is, D2D can be used for purposes other than caching, and caching can be attained without D2D [5]. The former case is manifested when activating D2D communications during the failure of the cellular network as a result of a natural or man-made disaster. The latter case is manifested when caching is attained in the infrastructure of the cellular network or at servers at the edge of the network near the end user.

The main contribution of this article is designing and analyzing a double edged scheme, shown in Figure (1), to mitigate the interference caused to the cellular user at the BS by D2D communications underlaying the cellular uplink channels. One edge of the scheme is a guard zone [6] prohibiting D2D communications in the vicinity of the BS. The other edge is a limit on the distance between the two devices of a D2D pair. The two devices can pair with each other only if the distance between them does not exceed this limit. This ensures that the pair will use minimal transmit power, thus exporting minimal interference to the BS. Actually, a feature technique of the article is devising an algorithm that takes the desired interference as input and gives the distance limit as output. Stochastic geometry [7] is the main tool for the present work. It is used to build the model for both the cellular network and the underlaying D2D network [8]. This model is then employed to characterize the coverage probability for the cellular user, a major indicator of its ability to operate unhindered by the interference generated by the ongoing D2D communications.

The implementation of the proposed scheme is extremely easy, requiring no hardware or software modifications in the UE. All that is needed is programming two distances in the UE: the radius of the guard zone and the inter UE distance limit. If the UE is closer to the UE than the former, or closer to the UE required for pairing up than the latter, this UE should not engage in D2D communications.

The rest of the article is organized as follows. In the next section, a review of related work is provided. In Section 3, the system model and proposed scheme are presented. Numerical results are given in Section 4, and concluding remarks in the last section.

2. Related Work

Much research has focused on the role of D2D to support caching of popular files, especially videos. For example, in [15], the authors investigate the optimal caching scheme for D2D networks with multiple robot helpers, with emphasis on large files. In [16], the authors study mobility-aware coded caching in D2D communication networks, exploiting multicasting opportunities for reducing network traffic. A transparent cache architecture to improve content delivery by Internet Service Providers (ISP) was proposed in [1], whereas a collaborative hierarchical

Table 1. Guard zone comparison: state of the art approaches and our approach

Ref.No.	Analysis Tool	Modelling Process	Results	Feature
[9]	SG	PPP	Outage probability	Transmission scheduling
[8]	SG	PPP	Coverage probability	Retention probability
[10]	SG	PHP	Coverage probability	Multi-tier HetNet
[11]	SG	PPP	Coverage probability	Decentralized access
[12]	SG	PHP and TCP	Coverage probability Area spectral effciency	D2D clusters
[13]	SG	PHP	Coverage probability Transmission probability	Energy harvesting
[14]	SG	PPP	Outage probability	Multi-tier HetNet
Ours	SG	PPP	Coverage probability	Empirical D2D distance limit

caching in edge networks was proposed in [2]. Edge caching was also considered in [17], where the authors propose a secure D2D caching framework leveraging trust management and blockchain in the context of video streaming. Video streaming was also condiered in [18], where the authors propose an iterative streaming algorithm for D2D networks. In [4] a new performance metric is introduced, namely the Service Success Probability, which captures the specificities of D2D networks for cache delivery. The authors of [4] proposed a new performance metric, the Service Success Probability, which captures the specificities of D2D networks for cache delivery. The impact of user mobility on caching was the focus in [19], where the authors propose mobility-aware schemes to turn the mobility challenge into an opportunity to reduce latency. In [20], the authors discuss proactive caching in D2D assisted multitier cellular networks, leveraging a support vector machine to predict the content popularity to determine which content is to be cached and where it is to be stored. In [21], the authors seek an optimal caching policy for D2D assisted cellular networks with different cache size devices.

AI tools, such as machine learning and optimization, have been utilized to optimize the operation and resource allocation of D2D communications and their use in caching. In [22], the authors propose sequence-to-sequence learning for link-scheduling in D2D communication networks. In Ioannou22 [23], the authors propose a distributed AI framework with ML for D2D communication in 5G/6G networks, based on agents that reside on the mobile devices (UEs). In Kou23 [24], the authors propose a hybrid particle swarm optimization-based model to address the problem of insufficient coverage. Machine learning and optimization are also used in resource allocation of D2D communications. For example, in [25], the authors study optimal resource allocation in the context of the Internet of Things. In Sun22 [26], the authors study resource allocation and power control based on noncooperative game for D2D communications underlaying cellular networks. A distributed resource allocation algorithm that combines the spectrum allocation and the power control and that is based on game theory and Nash equilibrium is used maximize the throughput. In Hakami22 [27], the authors study a resource allocation scheme for D2D communications with unknown channel state information. They use for that a graph-theoretic weighted bipartite matching (WBM) approach together with a multi-armed bandit formalism from machine learning theory. In [28], the authors find that reusing the same resources, the underlying D2D communication may cause high interference to cellular users, thus reducing the network throughput. To alleviate this issue, they consider moving D2D users to an unlicensed band and propose techniques to achieve that. A survey of resource management in general may be found in [29].

Analysis and improvement of the performance of D2D communications has been the subject of a great deal of research. In [30], enhancement of cellular networks via clustering in the context of mission-critical applications was considered. In Zhu22 [31], the authors study the performance of the uplink in cellular network with power control and the performance of this D2D network for different content availability cases. A substantial body of work in this field focused on interference as a means of performance improvement as in [32], where the authors study Interference management based on meta-heuristics such as Genetic Algorithms, Particle Swarm Optimization, and Bee Life Algorithm. Some work has been done with an eye to energy efficiency of D2D communications, as in

[33], where the authors propose a method to decrease total energy usage while simultaneously ensuring that Quality of Service (QoS) requirements are met. Discovery and collisions of D2D users has been discussed in [34].

The guard zone approach to mitigating interference in D2D underlaid cellular networks, which is the theme of the present work, has been investigated using stochastic geometry in several studies. In [9], a guard zone-based ad hoc network is studied using a PPP. The authors propose a scheduling technique that suppresses transmissions by nodes around the desired receiver, characterzing at the end the outage probability, which is the complement of the coverage probability characterized in the present work. In [8], the authors study coverage for D2D enabled cellular networks with guard zone using a PPP and impose a user defined limit on the distance between D2D users. In [10], the authors study heterogeneous wireless networks with a guard zone for the first-tier network, using Poisson hole process (PHP), characterizing at the end the coverage probability. In [11], the authors study decentralized opportunistic access for D2D underlaid cellular networks. They combine a SIR-aware link activation technique with guard zone, where D2D users opportunistically use the UL channel. Using a PPP, they characterize the coverage probability and study the impact of the guard zone radius and the SIR threshold on the D2D the spectral efficiency and cellular coverage. In [12], the authors provide a performance analysis of D2D underlaying cellular networks, assuming the UEs are located in hotspots and cell edges. For the analysis, they integrate PHP with Thomas Cluster Process (TCP). The study clumonates with expressions for the coverage probability and area spectral efficiency. In [13], the authors investigate energy-harvesting-based D2D communications, and consider lowering interference at the BS by both controlling the UE power and setting a guard zone. They use a PHP to characterize the transmission probability, D2D outage probability, and successful transmission probability. In [14], the authors also use a PPP to study outage probability for D2D-enabled heterogeneous cellular networks with guard zone.

3. System Model

In this section we develop an analytical framework for the proposed scheme, which is aimed at minimizing the interference inflicted on the cellular user by the D2D users. The framework accounts for the two elements of the scheme, the guard zone [6] and the distance limit imposed on the separation between any two devices wishing to form a D2D pair [8].

Figure 1 shows the model of the system under consideration. There is a circular cell of radius $\mathcal{R}$ with a base station (BS) at its center, together with a number of users, each having a user equipment (UE). These users will be modelled as a Poisson point process (PPP) Φ of density λ. We will classify a user based on its way of communications. If the communications are through the cellular network infrastructure, it is called a cellular user. If the communications are direct, without using the cellular network infrastructure, it is called a D2D user. Both types of users use the same cellular uplink frequency. As such, the problem is the interference exported by the D2D users to the cellular user, and the scheme proposed in this article is intended to mitigate this problem via two precautions. First, there is circular guard zone of radius $\mathcal{R}_0 < \mathcal{R}$, co-centered with the cell, surrounding the BS, within which D2D are prohibited. This ensures that the D2D communications do not take place near the center of the cell, causing sizable interference at the BS. Second, there is a limit $\mathcal{D}$ on the distance separating two users, above which the two users should refrain from communicating directly D2D. That is, the two UEs of every D2D pair should be at most $\mathcal{D}$ meters away from each other. This ensures that the two devices do not user large transmit power, causing sizable interference at the BS.

The transmit power of the cellular is $\mathfrak{p}$ and that of the D2D user is $\mathfrak{p}_D$. We should like to have $\mathfrak{p}_D << \mathfrak{p}$ for two reasons. The first is to conserve the energy of the D2D nodes. The second, which is more relevant to the present work, is to reduce the D2D interference to the cellular user at the BS.

As for the channel model, we will consider Rayleigh fading and with power-law path loss, with path loss exponent $\alpha > 2$. In other words, the mean received power at distance r away from a UE of power $\mathfrak{p}_D$ will be $\mathfrak{p}_D r^{-\alpha}$. We will incorporate random channel effects by a multiplicative RV G_z for a UE located at point z. The G_z are assumed independent and identically distributed (iid), following an exponential distribution with mean 1. That is, $G \sim \exp(1)$ and $G_z \sim \exp(1)$. The RV G_z for the cellular user will be denoted by G for simplicity.

As mentioned above, reducing this interference is the objective of this work, and is reached via a double-element scheme. The first element of the scheme is a guard zone surrounding the BS, whose function is to push the D2D communications away from the BS. The second element is restricting pairing up for D2D communications to any two devices the distance between them being less than a predefined limit. To achieve the objective, we leverage stochastic geometry and Monte Carlo simulation. Both tools are used to obtain the said distance limit and the corresponding thinning probability, necessary to characterize the cellular user's coverage probability, which is the main metric to measure the success of the proposed scheme. The coverage probability is defined as the probability that the signal-to-interference ratio (SIR) at the BS exceeds a certain desired threshold ξ. Finally, for convenience, a list of the notation used in this article is provided in Table 2.

Table 2. Notation used in the model and simulation.

Notation	Description
$\mathcal{R}$	Cell Radius
$\mathcal{R}_0$	Guard Zone Radius
$\mathcal{D}$	Distance between two arbitrary D2D users
R_z	Distance between D2D user and BS
R	Distance between cellular user and BS
SIR	Signal to interference ratio (dB)
ξ	SIR threshold (dB)
Φ	Poisson point process (PPP) representing D2D devices
λ	Intensity of Φ (per m^2), i.e. density of D2D devices
$\widetilde{p}$	PPP thinning probability
$\Phi^{\widetilde{p}}$	Thinned PPP
D	Limit distance for D2D pairing
$\mathfrak{p}$	Transmit power of cellular user
$\mathfrak{p}_D$	Transmit power of D2D user
α	Path loss exponent
p_u	Uplink coverage probability of cellular user
$\mathbf{D}$	Array of potential distances $[\mathsf{D}_j]$ to find distance limit D
ϵ	Tolerance of difference between simulation and analytical thinning probabilities
p_s	Simulation thinning probability

To develop an analytical model, based on stochastic geometry, we will consider one cellular user located in the cell at some point (R, Θ), where R and Θ are each a uniformly distributed random variable (RV), with $0 < R \leq \mathcal{R}$ and $0 < \Theta \leq 2\pi$. The uniform distribution of Θ implies that

$$f_\Theta(\theta) = \frac{1}{2\pi}. \tag{1}$$

On the other hand, to find the uniform distribution of R, consider a point at distance $R = r$ from the center of the cell. The cumulative distribution $F_R(r) = \mathbb{P}[R \leq r]$ of R is clearly given by

$$F_R(r) = \frac{\pi r^2}{\pi \mathcal{R}^2} = \frac{r^2}{\mathcal{R}^2}.$$

Differentiating, we get the distribution of R as

$$f_R(r) = \frac{d}{dr} F_R(r) = \frac{2r}{\mathcal{R}^2}. \tag{2}$$

Doing the same for a D2D user located in the ring $\mathcal{R}_0 < R_D \leq \mathcal{R}$ at a distance R_D away from the BS, we get

$$f_{R_z}(r) = \frac{2r}{\Delta \mathcal{R}}. \tag{3}$$

where $\Delta\mathcal{R} = \mathcal{R}^2 - \mathcal{R}_0^2$.

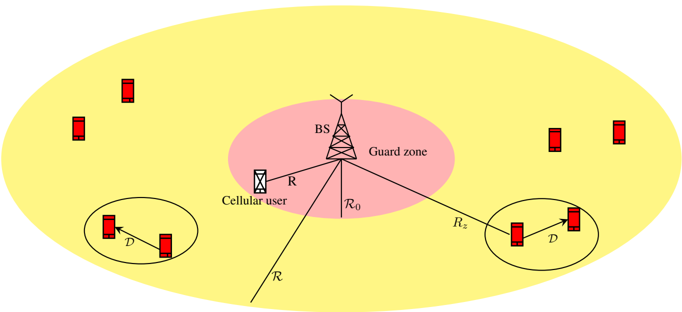

Figure 1. Cell with a guard zone, where D2D communications is not allowed. Outside the guard zone, two UEs can form a D2D pair only if the distance $\mathcal{D}$ between them does not exceed the limit D.

The Laplace functional for a PPP of intensity λ corresponding to a real valued function f defined on $\mathbb{R}^d$ is given [35] by

$$\mathcal{L}_\Phi(f) = e^{-\int_{\mathbb{R}^d}(1-e^{-f(x)})\lambda dx}, \tag{4}$$

The PPP Φ represents all the UEs in the cell, while we would like now to find a representation for only those of them that will participate in D2D communications, but only those satisfying the distance limit. Accordingly, all the other devices, those that exceed the limit, will be excluded from the PPP. Analytically, this means that only a *portion* of the points of the original PPP is will be considered, removing all other points. When removing points from a certain PPP of some density λ, the remainder is still a PPP but with a smaller density $\widetilde{p}\lambda$, where $\widetilde{p} < 1$ is called the thinning probability. This probability is luckily given [35] by

$$\widetilde{p} = 1 - e^{-\kappa\pi\lambda \mathsf{D}^2}, \tag{5}$$

where κ is a tuning factor set to reflect the proper thinning amount. The value $\kappa = 0.8$ is empirically found [8] to give reasonable results for the range of UE density λ commonly considered in practical cellular network deployment. With this probability at hand, one can write the Laplace functional of the thinned process as

$$\mathcal{L}_{\Phi^{\widetilde{p}}}(f) = e^{-\int_{\mathbb{R}^d}(1-e^{-f(x)})\widetilde{p}\lambda dx}, \tag{6}$$

So, the task now is to find the adequate D2D distance limit D, necessary to reduce the D2D power and hence the D2D interference at the BS, together with the corresponding PPP thinning probability $\widetilde{p}$ that captures the representation of only the D2d users. This task, considered the main contribution of the article, will be completed by the novel algorithm in Figure 2, considered the main contribution of the article.

The idea of the algorithm is to try a certain distance limit, e.g. $\mathsf{D} = 5$ m. Practically, this means that when two devices discover that they are 5 m or less apart, they then can engage in a D2D communications session. Otherwise, they will refrain from communicating together. So, the algorithm in effect calculates the thinning probability corresponding to that distance, both analytically, $\widetilde{p}$, using 5, and by simulation, p_s, using a suitable stochastic geometric approach [36]. If the relative difference between the two values are within an acceptable tolerance ϵ, it means that the current distance $\mathsf{D} = 5$ matches the analytical value of the thinning probability $\widetilde{p}$, which in turn means that there is room to try a larger distance, e.g. $\mathsf{D} = 10$ m. This procedure is repeated until a mismatch occurs, at which point the algorithm stops and considers the preceding distance to be the distance limit D. For example, suppose that the algorithm finds a mismatch at 70 m, while the preceding distance that resulted in a match was $\mathsf{D} = 65$ m. In this case, the distance limit for D2D communications in this system is 65 m.

To automate the running of the Algorithm, a list $\mathbf{D}$ of suggested distance limits, sorted ascendingly, is read upfront. The values of these list are then tried one by one, starting with the first value, till the value that causes a mismatch is hit, at which time the Algorithm exits and prints both the matching distance and the corresponding thinning probability.

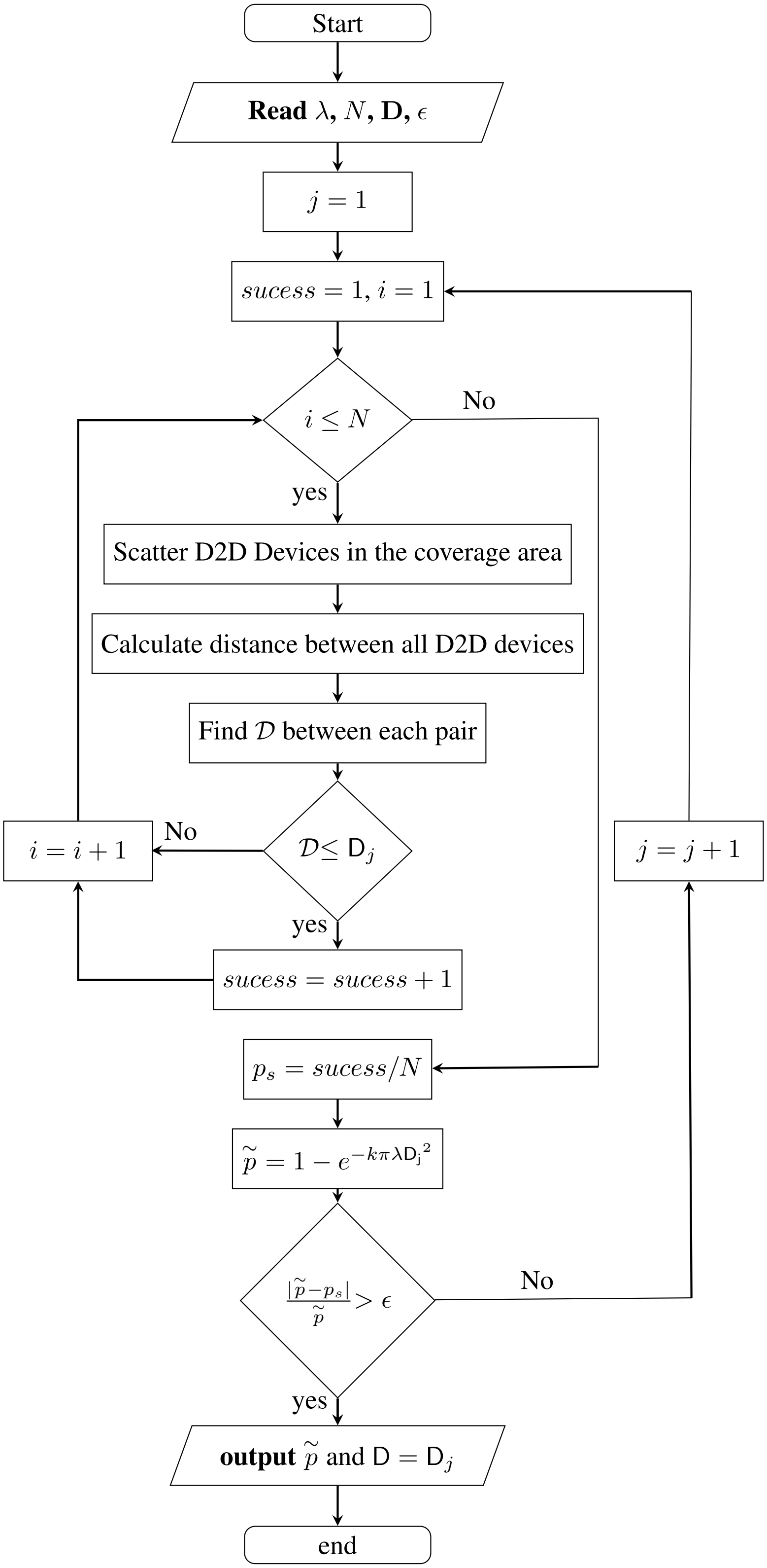

Figure 2. Algorithm to find the D2D distance limit, D, and the corresponding thinning probability, $\widetilde{p}$.

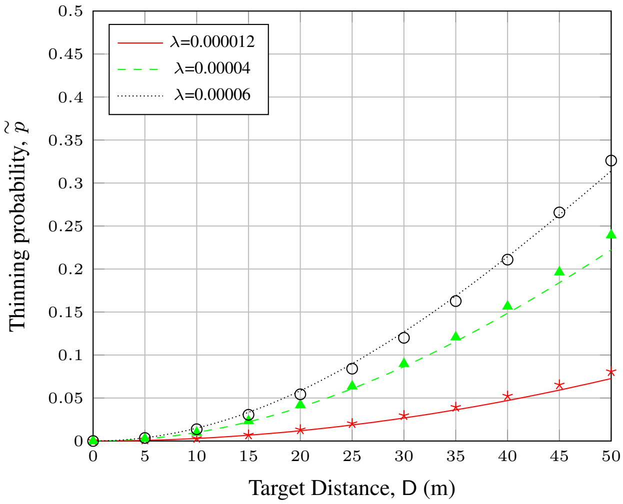

Figure 3. Thinning Probability vs distance limit for three values of λ.

Figure (3) shows the result of running the algorithm for a list $\mathbf{D}$ of suggested limits, ranging from 5 m to 100 m, for 3 values of λ and a tolerance $\epsilon = 0.05$. The mismatch between the analytical and simulation values of the thinning probability occurred at $\mathbf{D} = 50$. The three corresponding thinning probability values, for the three values of the PPP intesnity λ, are as shown in the Figure, and are used in the sequel.

With the above in mind, It is time now to characterize the coverage probability for the cellular user under the proposed scheme, which includes the guard zone and the D2D inter-pair distance limit. To this end, let I_D be a RV denoting the interference at the BS that is caused by all D2D users and harming the uplink signal of a cellular user. This interference I_D is due to every D2D device z in the ring outside the guard zone at distance R_z, $\mathcal{R}_0 < R_z \leq \mathcal{R}$, from the BS, as shown in Figure 1. Based on the above, this interference is given by

$$I_D = \sum_{z \in \Phi} p_D G_z R_z^{-\alpha}, \tag{7}$$

The SIR at the BS is thus given by

$$\texttt{SIR} = \frac{pGR^{-\alpha}}{I_D}, \tag{8}$$

Now, the goal is to derive an expression for the uplink coverage probability defined as

$$p_u = \mathbb{P}[\texttt{SIR} > \xi], \tag{9}$$

where ξ is a positive real number representing the desired SIR threshold.

Using (7) and (8) in (9), the uplink coverage probability can be written as

$$\begin{aligned} p_u &= \mathbb{P}\left[\frac{pGR^{-\alpha}}{I_D} > \xi\right] \\ &\overset{(a)}{=} \mathbb{E}_{I_D}\left[\mathbb{P}\left[G > \frac{\xi}{p} R^{\alpha} I_D\right]\right] \\ &\overset{(b)}{=} \mathbb{E}_{I_D}\left[e^{-\frac{\xi}{p} R^{\alpha} I_D}\right] \\ &= \mathcal{L}_{I_D}\left(\frac{\xi}{p} R^{\alpha}\right) \end{aligned} \tag{10}$$

where for any RV A the expectation

$$\mathcal{L}_A(s) = \mathbb{E}\left[e^{-sA}\right] = \int_0^{\infty} e^{-st} f_A(t)dt \tag{11}$$

is the Laplace transform of (the distribution of) A. In (a) we exploited the fact that we can write the probability $\mathbb{P}[A > B]$ as $\mathbb{E}_B[\mathbb{P}[A > B]]$ (or $\mathbb{E}_A[\mathbb{P}[A > B]]$), and in (b) we made use of the fact that $G \sim \exp(1)$, i.e. $f_G(r) = e^{-r}$. We will now embark on deconditioning (averaging) (10) on all the RVs involved.

Deconditioning p_u on R, which is uniformly distributed as given by (3), we get

$$\begin{aligned} p_u &= \int_0^{\mathcal{R}} \mathcal{L}_{I_D}(\frac{\xi}{p} r^{\alpha}) f_R(r) dr \\ &= \frac{2}{\mathcal{R}^2} \int_0^{\mathcal{R}} \mathcal{L}_{I_D}(\frac{\xi}{p} r^{\alpha}) r dr \end{aligned} \tag{12}$$

Next, we decondition $\mathcal{L}_{I_D}$ on the G_z and Φ, with the latter via the PGFL. From (7) and (11), we get

$$\begin{aligned} \mathcal{L}_{I_D}(s) &= \mathbb{E}\left[e^{-sI_D}\right] \\ &= \mathbb{E}_{\Phi, G_z}\left[e^{-s\sum_{z\in\Phi} p_D G_z R_z^{-\alpha}}\right] \\ &\overset{(a)}{=} \mathbb{E}_{\Phi}\left[\prod_{z\in\Phi} \mathbb{E}_{G_z}\left[e^{-sp_D G_z R_z^{-\alpha}}\right]\right] \\ &\overset{(b)}{=} \mathbb{E}_{\Phi}\left[\prod_{z\in\Phi\setminus\{\mathfrak{b}\}} \mathcal{L}_{G_z}(sp_D R_z^{-\alpha})\right] \\ &\overset{(c)}{=} \exp\left(-\lambda\widetilde{p} \int_{\mathbb{R}^2\setminus D(O,\mathcal{R}_0)} f(\mathcal{L}_{G_z})\right) \end{aligned} \tag{13}$$

where $f(\mathcal{L}_{G_z}) = 1 - \mathcal{L}_{G_z}(sp_D R_z^{-\alpha})$ and $D(O, \mathcal{R}_0)$ is the disk centered at the origin (BS) with radius $\mathcal{R}_0$. This disk an exclusion zone, as the points of the PPP Φ lie outside of it. In (a) we exploited the assumption that the G_z are independent, and in (b) we made use of the definition (11) of the Laplace transform. In (c), we invoked The probability generating functional (PGFL) for a function $f(R_z) = \mathcal{L}_{G_z}(sp_D R_z^{-\alpha})$ with thinning probability $\widetilde{p}$ from (4) implies that

$$\begin{aligned} E\left[\prod_{z\in\Phi} f(R_z)\right] &= e^{-\int_{\mathbb{R}^2}(1-f(R_z))\widetilde{p}\lambda dz}, \\ &= e^{-2\pi\lambda\widetilde{p}\int\limits_0^{\infty}(1-f(R_z))zdz}, \end{aligned} \tag{14}$$

With $f(R_z) = \mathcal{L}_{G_z}(sp_D R_z^{-\alpha})$, decondition now on the function $\mathcal{L}_{G_z}(sp_D R_z^{-\alpha})$ at all the points z of the PPP Φ. Although the points of the PPP exist everywhere in the Euclidean plane, we will consider only those in the ring bounded by the two radii $\mathcal{R}_0$ and $\mathcal{R}$. Using polar coordinates, and the fact that $f_{G_z}(t) = e^{-t}$ so that $\mathcal{L}_{G_z}(s) = 1/(1+s)$, the Laplace transform on the RHS of (13) yields

$$\mathcal{L}_{G_z}(sp_D R_z^{-\alpha}) = \frac{1}{1 + sp_D R_z^{-\alpha}}$$

Substituting this in (13), with the interferer now at a specific point (x, θ), we get

$$\begin{aligned} \mathcal{L}_{I_D}(s) &= \exp\left(-\lambda\widetilde{p} \int_{\mathcal{R}_0}^{\mathcal{R}} \int_0^{2\pi} \mathcal{L}_{G_z}(sp_D R_z^{-\alpha}))d\theta x dx\right) \\ &= \exp\left(-2\widetilde{\lambda}\widetilde{p} \int_{\mathcal{R}_0}^{\mathcal{R}} (\frac{sp_D x^{-\alpha}}{1 + sp_D R_z^{-\alpha}}) x dx\right), \end{aligned}$$

where $\widetilde{\lambda} = \lambda\pi$.

Now we will decondition $\mathcal{L}_{I_D}(s)$ on the R_z which are uniformly distributed as per (3) to get

$$\begin{aligned}\mathcal{L}_{I_D}(s) = &\quad \exp\left(-2\widetilde{\lambda}\widetilde{p}\int_{\mathcal{R}_0}^{\mathcal{R}}\int_{\mathcal{R}_0}^{\mathcal{R}}\frac{sp_D x^{-\alpha}}{1+p_D y^{-\alpha}}f_{R_z}(y)dyxdx\right)\\ = &\quad \exp\left(-\frac{4\widetilde{\lambda}\widetilde{p}}{\Delta\mathcal{R}}\int_{\mathcal{R}_0}^{\mathcal{R}}x^{-\alpha}\int_{\mathcal{R}_0}^{\mathcal{R}}\frac{sp_D y}{1+sp_D y^{-\alpha}}dyxdx\right).\end{aligned}$$

Accordingly, we can write

$$\begin{aligned}\mathcal{L}_{I_D}(\frac{\xi}{p}r^{\alpha}) = &\quad \exp\left(-\frac{4\widetilde{\lambda}\widetilde{p}}{\Delta\mathcal{R}}\int_{\mathcal{R}_0}^{\mathcal{R}}\left(\int_{\mathcal{R}_0}^{\mathcal{R}}\frac{\frac{\xi}{p}r^{\alpha}p_D x^{-\alpha}}{1+\frac{\xi}{p}r^{\alpha}p_D y^{-\alpha}}ydy\right)xdx\right)\\ = &\quad \exp\left(-\frac{4\widetilde{\lambda}\widetilde{p}}{\Delta\mathcal{R}}\int_{\mathcal{R}_0}^{\mathcal{R}}\left(\int_{\mathcal{R}_0}^{\mathcal{R}}\frac{\frac{\xi}{p}\left(\frac{r}{x}\right)^{\alpha}p_D}{1+\frac{\xi}{p}\left(\frac{r}{y}\right)^{\alpha}p_D}ydy\right)xdx\right)\end{aligned}$$

Substituting this in (12) we get our final result

$$\begin{aligned}p_u &= \frac{2}{\mathcal{R}^2}\int_0^{\mathcal{R}}\mathcal{L}_{I_D}(\frac{\xi}{p}r^{\alpha})rdr\\ &= \frac{2}{\mathcal{R}^2}\int_0^{\mathcal{R}}e^{-\frac{4\widetilde{\lambda}\widetilde{p}}{\Delta\mathcal{R}}\int_{\mathcal{R}_0}^{\mathcal{R}}\left(\int_{\mathcal{R}_0}^{\mathcal{R}}\frac{\frac{\xi}{p}\left(\frac{r}{x}\right)^{\alpha}p_D}{1+\frac{\xi}{p}\left(\frac{r}{y}\right)^{\alpha}p_D}ydy\right)xdx}rdr\end{aligned} \tag{15}$$

4. Numerical Results

To test the proposed scheme, in this section we will calculate the coverage probability, using the analytical expression given by (15) for several example systems. However, to validate the analytical results, the same systems have been simulated using the MATLAB language. A cell radius $\mathcal{R} = 4000$ m and a D2D pairing distance limit $\mathrm{D} = 50$ m are used in all examples. For each example system, $N = 10000$ simulation runs were performed. This number was found enough to reach satisfactory convergence. As the figures below show, there is good match between the analytical and simulation results.

Figure (4) shows the relationship between the coverage probability of the cellular user and the guard zone radius, for three values of the UE density, λ. Both analytical resulsts (lines) and simulation results (bullets) are shown, with good match between the two. As can be seen, the larger the guard zone radius, the larger the coverage probability, which is logical. After all, as we push the D2D users away from the BS, by the guard zone, the interference reaching the BS diminishes. The increase in the probability with the radius becomes more nonlinear, however, as the density increases, tapering off as the radius of the zone approaches that of the cell, $\mathcal{R} = 4000$ m. Regarding, the relationship with the UE density, it can be seen that the higher the density the lower the coverage, which is also logical. After all, the larger the density of all the UEs, the larger the ratio participating in D2D communications, the more the interference inflicted on the cellular user, and hence the smaller the coverage.

Figure (5) shows also the relationship between the coverage probability of the cellular user and the guard zone radius, for three values of the SIR threshold, ξ. Comments similar to those of (4) apply here, especially for the relationship between the coverage and the guard zone radius. Regarding, the relationship with the SIR threshold, it can be seen that the higher the threshold the lower the coverage, which is also logical. After all, the threshold specifies our expectations of what can be called high coverage. If we raise our standard for high coverage, specifying high threshold, the present coverage may fall short of meeting that standard, and vice versa.

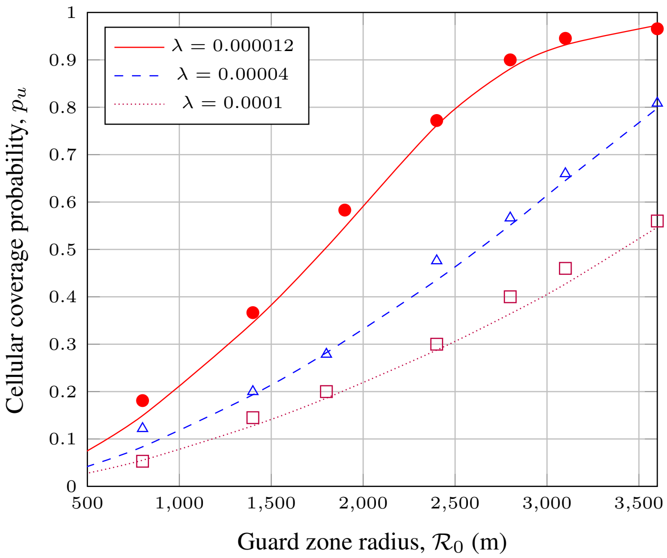

Figure 4. Coverage probability vs guard zone radius for three UE density values, both analytical (lines) and simulation (bullets). The SIR threshold is $\xi = -10$ dB.

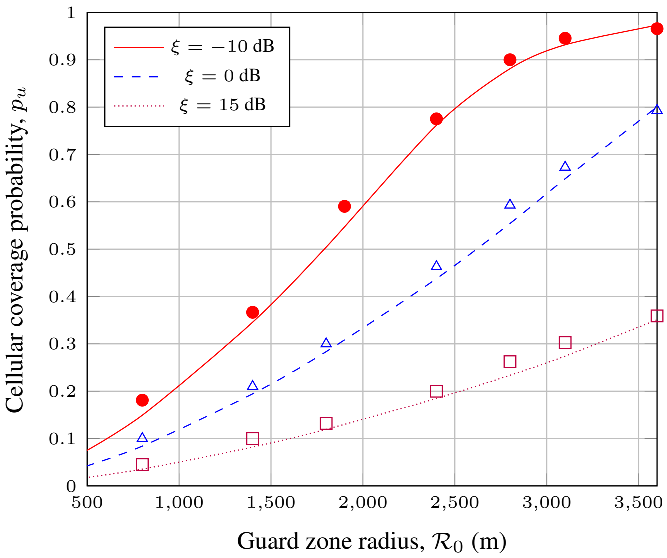

Figure 5. Coverage probability vs guard zone radius for three SIR threshold, both analytical (lines) and simulation (bullets). The UE density is $\lambda = 0.000012$.

5. Conclusions

In this article an integrated scheme has been proposed to improve the performance of a D2D-assisted cellular network. The strategy of the scheme is based on minimizing the interference caused by D2D users to the cellular user. The scheme achieves this strategy by two approaches, keeping D2D users sufficiently far from the cell's BS and keeping the communicating D2D users close enough to each other. The first approach decreases the interference received at the BS, whereas the second approach decreases the interference transmitted at the D2D devices. The feasibility of the scheme has been verified by intensive experiments carried out on a simulator developed using the MATLAB language.

For possible future extensions of the present work, there are many interesting avenues. For example, besides the Rayleigh channel model considered in the present work, one can consider other popular models, such as log-normal, Nakagami-m, Rice and Weibull. Further, it would be highly enticing, albeit challenging, to investigate the impact of mobility of D2D users on the performance of the guard zone. Last but not least, it would be glamorous to incorporate machine learning somehow in the scheme, say for the determination of the limit of the admissible D2D communications distances.

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